Investigation of extreme flows in Cyprus: empirical formulas and regionalization approaches for peak flow estimation (1)

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Session HS4.1/NH1.11: *Flash floods: observations, modeling, forecasting and risk management*

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1. Abstract

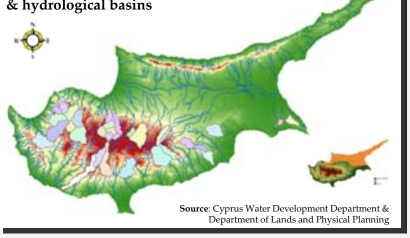
The island of Cyprus has a typical Mediterranean, semi-arid climate, characterized, among others, by relatively short yet intense storm events causing flash floods. Current practices for the design of flood-protection works as well as flood risk assessment are based on regional approaches, which require a number of parameters that derive from the river basin characteristics. The main target of this work is to evaluate the existing empirical formulas for estimating those watershed parameters, emphasizing on the runoff coefficient and the time of concentration, which are typical inputs for most of the aforementioned tools, such as the rational and the unit hydrograph methods. For this purpose, we analyzed a large amount of hydrological and geographical data, provided by the Water Development Department and the Meteorological Service of Cyprus. This includes annual discharge maxima at 130 flow gauges and the corresponding rainfall data, intensity-duration-frequency (ombrian) curves for different regions of the island, and geographical information for 70 river basins (DEM, hydrographic network, land uses, geology and permeability). A preliminary statistical analysis of annual maxima data indicated that the empirical distribution functions of the flood discharges are much sharper than those of the corresponding rainfall depths, which denotes strongly nonlinearity of the rainfall-runoff mechanisms. In addition, we found that the existing peak runoff estimation methods fail to reproduce this kind of nonlinearity, thus leading to severe underestimation of flood risk. To handle this inconsistency it was necessary to revise the erroneous hypothesis that both the runoff coefficient and the time of concentration are constant properties of the basin. In reality, they depend not only to the constant geomorphological characteristics of the basin but also to the rainfall-runoff event itself. However, an analytical estimation of their actual values is impossible, since they are related to complex hydrological and hydraulic processes. For this reason, we examine the simple yet realistic assumption that the two variables are functions not to the event magnitude but to its return period. Using appropriate historical data, we attempt to establish improved empirical relationships for Cyprus, by fitting the simulated peak flow values to the observed ones.

2. Outline of the methodology

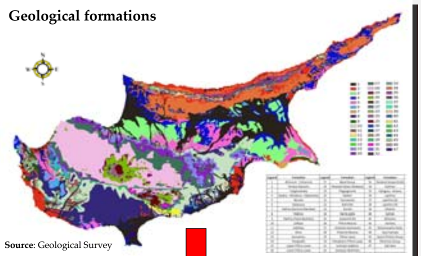
1. **Retrieval of raw spatial and hydrological information**
   - Geographical data (DEM, land cover, geology, etc.);
   - Areal IDF curves (four sets, assigned to different regions);
   - Maximum observed flows per month at 118 flow stations.
2. **Data analysis and processing**
   - Production of geographical layers (slope, permeability, CN);
   - Selection of 34 out of 119 sub-basins, for further analysis;
   - Estimation of physiographic properties per sub-basin (area, characteristic elevations, characteristic slopes, characteristic lengths of the main river course, river network density);
   - Estimation of hydrological properties per sub-basin (runoff coefficient, curve number and time of concentration, using different approaches);
   - Statistical analysis of the annual flow maxima and fitting of distribution functions.
3. **Validation of the rational method**
   - Selection of 32 flood events that are convenient with the assumptions of the rational method;
   - Assignment of a suitable return period to each event;
   - Application of the rational formula, testing different values of the time of concentration;
   - Evaluation of results and selection of the most suitable model for the time of concentration.
4. **Investigation of improved configurations of the rational formula**
   - Formulation of various parametric relationships for the time of concentration;
   - Formulation of correction formulas for the runoff coefficient and the time of concentration, as functions of the return period;
   - Calibration of the aforementioned models against the observed peak flows and selection of the most appropriate one.

3. Geographical data and processing

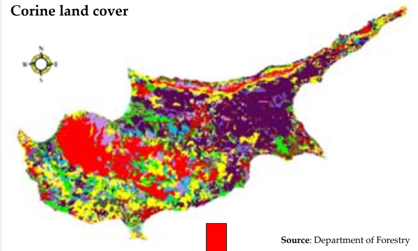
Digital elevation model, drainage network & hydrological basins



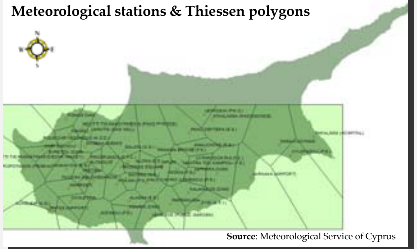
Geological formations



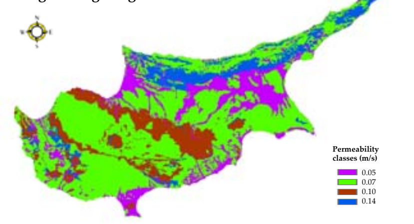
Corine land cover



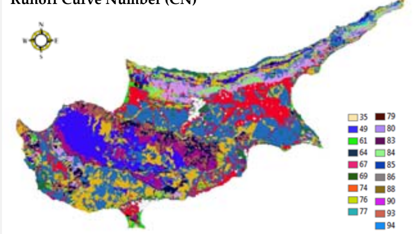
Meteorological stations & Thiessen polygons



Categorized geological formations



Runoff Curve Number (CN)

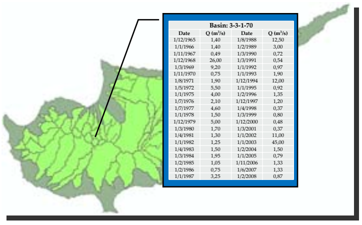


4. Analysis of maximum flow data

The Water Development Department of Cyprus, which maintains a network of 118 flow gauges in the southern part of the island, provided a record of 2339 monthly maximum discharge values, from which we extracted the annual maxima.

Next, we selected 34 stations for further analysis, according to the following criteria:

- the upstream area is not urbanized neither contains major hydraulic structures (e.g. dams);
- the length of data is at least 20 years;
- the size of the basin is at least 5.0 km².



Basin: 3-3-1-70

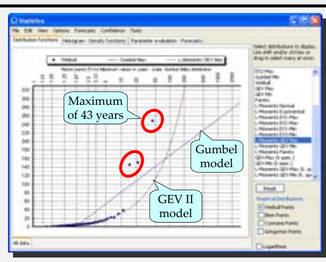
Date	Q (m³/s)	Date	Q (m³/s)
1/12/1965	1,40	1/8/1988	12,50
1/1/1966	1,40	1/2/1989	3,00
1/11/1967	0,49	1/3/1990	0,72
1/12/1968	26,00	1/3/1991	0,54
1/3/1969	9,20	1/1/1992	0,97
1/11/1970	0,75	1/1/1993	1,90
1/8/1971	1,90	1/12/1994	12,00
1/5/1972	5,50	1/1/1995	0,92
1/1/1975	4,00	1/2/1996	1,35
1/7/1976	2,10	1/12/1997	1,20
1/7/1977	4,60	1/4/1998	0,37
1/1/1978	1,50	1/3/1999	0,80
1/12/1979	5,00	1/12/2000	0,48
1/3/1980	1,70	1/3/2001	0,37
1/4/1981	1,30	1/1/2002	11,00
1/1/1982	1,25	1/1/2003	45,00
1/4/1983	1,50	1/2/2004	1,50
1/3/1984	1,95	1/1/2005	0,79
1/2/1985	1,05	1/11/2006	1,33
1/2/1986	0,75	1/6/2007	1,33
1/1/1987	3,25	1/2/2008	0,87

Finally, we selected the 32 most important flood events, on the basis of the dimensionless peak flow, using as threshold the 1.0 $m^3/s/km^2$.

5. Statistical investigation of flows

Using the **Hydrognomon** software, we plotted the empirical distribution functions of the 34 records of annual flow maxima, and fitted the most appropriate theoretical one; for all the cases we selected the Generalized Extreme Value II (GEV-II), by estimating its parameters via the L-moments method.

Although this distribution results in significantly higher risk that other typical models used in hydrology (e.g. the Gumbel distribution), it failed to capture the very extreme events of most of the stations, which indicates that the flood-generation mechanisms in Cyprus are highly non-linear.



Comparison of empirical and theoretical distribution functions for the station 2-2-6-60, where the return periods of the three highest annual maximum flows are definitely overestimated.

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6. The rational method for peak flow estimation

The method relates the peak discharge q_p to the rainfall intensity *i*, which corresponds to a specific return period *T* and a specific storm duration *d*, by the well-known relationship $q_p = c\, i\, A$, where *c* is the runoff coefficient and *A* is the drainage area (river basin or urban catchment).

The main assumptions under this widespread empirical approach are the following:

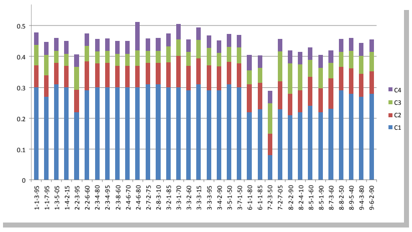
- the storm duration *d* equals or exceeds the time of concentration t_c of the basin;
- the rainfall is uniformly distributed over the basin;
- all hydrological deficits are incorporated into the runoff coefficient, which is typically treated as a constant property of the basin.

The rainfall intensity is easily estimated, if an idf (ombrian) curve is available for the basin under study. For a given return period *T*, and following the first of the assumptions, the duration of the rainfall event is taken equal to the time of concentration of the basin, i.e. $d = t_c$, thus *i* is computed as a function of *d* and *T*. In general, the time of concentration is also assumed a constant property of the basin, and is estimated using regional empirical approaches, accounting for a number of physiographic characteristics.

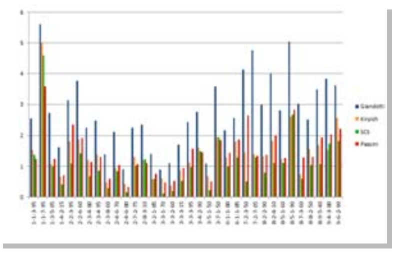
7. Estimation of sub-basin properties (runoff coefficient and time of concentration)

The **runoff coefficient** *c* is estimated according to the Directives for Roadwork Studies of Greece (OMOE), as the sum of four components that are related to the following characteristics:

- c_1: relief and slope;
- c_2: soil permeability;
- c_3: vegetation (Corine classification);
- c_4: soil drainage capacity.



Stacked columns comprising the four components of the runoff coefficient according to the OMOE directives, for the 34 basins under study.



Comparison of time of concentration values derived by four different empirical formulas, for the 34 basins under study.

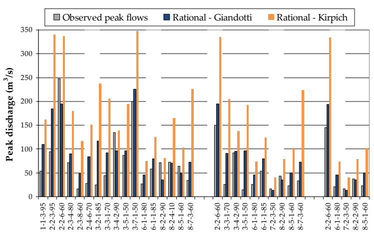
The **time of concentration** t_c is the most often used parameter to characterize the response of a basin to a rainfall event. A number of empirical formulas exist to evaluate t_c on the basis of characteristic geometrical and physiographic properties of the basin (typically area, slope and length of main tributary). In this study, we tested four "traditional" formulas, which are widely used in Cyprus:

- Giandotti (1937);
- Kirpich (1940);
- Soil Conservation Service (SCS, 1972);
- Passini (1914).

8. Evaluation of the rational method

For the alternative values of t_c, and assuming that the return period of rainfall coincides with the empirical return period of the maximum annual discharge (which is the length of the flow data, if we refer to the highest event), we used the idf curves, provided by the Meteorological Service of Cyprus, to estimate the rainfall intensity *i*. These curves have been recently updated, and their general parametric expression is:

$$i = \frac{\lambda^* \psi + \frac{\lambda}{\kappa}\left[\left(-\ln\left(1-\frac{1}{T}\right)\right)^{-\kappa} - 1\right]}{(t_c+\theta)^{\eta}}$$



a/a	Description	Time of concentration	CE
1	Kirpich	$t_c = 0.01947(L_{max})^{0.77}(S')^{-0.385}$	-3.45
2	Giandotti	$t_c = \frac{4A^{0.5}+1.5L}{0.8\Delta H^{0.5}}$	0.484
3	SCS	$t_c = \frac{L^{1.15}}{7700H^{0.38}}$	-4.02
4	Passini	$t_c = 0.108\frac{\sqrt[3]{A*L}}{\sqrt{S}}$	-4.04

To test the predictive capacity of the rational method we used the 32 highest events, to be as much consistent with its assumptions.

The results obtained by the four different formulas for the estimation of t_c were evaluated using as performance criterion the coefficient of efficiency (CE), given by:

$$CE = 1 - \sigma_e^2 / \sigma_y^2$$

where σ_e^2 is the variance of the residuals and σ_y^2 is the variance of the observed peaks.

Apart from the Giandotti formula, which achieves a marginally satisfactory efficiency of 48.4%, the rest of empirical methods for t_c are totally inappropriate for the Cyprus conditions, since they underestimate the time of concentration, thus providing too high discharge peaks. This is clearly indicated by the significantly negative efficiency values.

9. Improving the predictive capacity of the rational method by optimizing the existing time of concentration formulas

The investigations showed that the most important (and at the same time uncertain) parameter of the rational method is the time of concentration, which drastically affects the intensity of the design rainfall. Yet, the available methods (apart from the Giandotti) failed to provide reliable estimations of the peak flows, since their numerical coefficients have been derived from experimental basins with very different hydrological and climatic regime in regard to Cyprus. For instance, the Kirpich formula was developed from data obtained in seven very small rural watersheds in Tennessee, USA, having well-defined channels and steep slopes from 3 to 10%.

In this context, as first attempt to improve the applicability of the rational method in Cyprus, we used the mathematical structure of the two most common formulas (i.e., Giandotti and Kirpich) and we optimized their coefficients, against the same peak flow sample (32 values). The results are shown in the following table. As objective function we used the coefficient of efficiency.

Description	Time of concentration	CE
Optimized Giandotti	$t_c = \frac{10A^{0.5}+0.1L}{0.867DH^{0.5}}$	0.727
Optimized Kirpich	$t_c = \frac{2L^{0.38}}{3S^{0.18}}$	0.750

The two optimized formulas achieve much higher efficiency, namely 72.7% and 75.0% for the formulas of Giandotti and Kirpich, respectively – the latter is radically improved with regard to the original one, whose performance is extremely poor (CE = -345%).

10. Improving the structure of the rational method using risk-depended formulas for its parameters

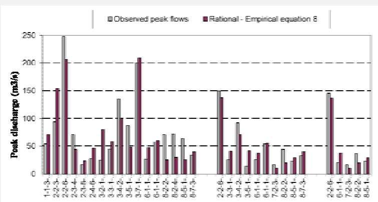
It is well-known that both the hydrological deficits, which are embedded into the runoff coefficient, and the time of concentration, are highly depended to both the rainfall and the resulting flow magnitude and their spatial and temporal distributions.

Specifically, the runoff coefficient should increase as the rainfall intensity increases, given that the infiltration capacity of the soil tends more rapidly to saturation.

With regard to the time of concentration, this is an expression of a characteristic length *L* of the drainage network to a characteristic velocity *u*. This last variable comprises a hillslope and a stream component, which are functions of the hydraulic properties of the basin and the discharge.

Yet, due to the complexity of the related processes, there is no sense to provide flow-depended formulas for the rational method parameters, which is nothing than a simple tool of the everyday engineering practice. On the other hand, provided that the peak discharge is a function of the probability of exceedence of the design rainfall, we attempted to develop new empirical formulas for *c* and t_c, which embed not only the physical properties of the basin but also the risk of hydrological design, by means of the return period *T*.

Description	Time of concentration	Runoff Coefficient	CE
Empirical Equation 1	$t_c = \frac{L}{3600\ u}$ $u = 2.22 m/s$	Regulations OMOE	-0.170
Empirical Equation 2	$t_c = \frac{L}{3600\ u}$ $u = 7.51\sqrt{S_{max}}$	Regulations OMOE	-0.290
Empirical Equation 3	$t_c = 0.617\sqrt{A}$	Regulations OMOE	0.727
Empirical Equation 4	$t_c = \frac{5.0A^{0.47}}{L_{max}^{0.73}}$	Regulations OMOE	0.798
Empirical Equation 5	$t_c = \frac{3.59A^{0.416}}{L^{0.404}}$ $t_c(T) = \frac{t_c}{T^{0.07}}$	Regulations OMOE	0.799
Empirical Equation 6	$t_c = \frac{121.76(A/L_{max})^{0.398}}{60S^{0.01}}$ $t_c(T) = \frac{t_c}{T^{0.2}}$	$c' = 0.5c$	0.790
Empirical Equation 7	$t_c = \frac{3.74(A/L_{max})^{0.258}}{\sqrt{S}*CN^{0.429}}$ $t_c(T) = \frac{t_c}{T^{0.2}}$	$c' = 0.5c$	0.760
Empirical Equation 8	$t_c = \frac{4.23(A/L_{max})^{0.429}}{\sqrt{S_{mean}}*CN^{0.20}}$ $t_c(T) = \frac{t_c}{T^{0.11}}$	$c(T) = 0.43c + 0.1\ln(T)$	0.797



In this context, we tested eight formulas of various levels of complexity, and calibrated their parameters, by maximizing their efficiency against the peak flow sample.

From the six approaches providing similarly satisfactory predictive capacity (eq. 3-8), we propose using the last one, taking into account both its performance (CE = 79.7%) and its physical interpretation. As shown in the adjacent chart, this approach represents very well most of the observed peaks.

11. Conclusions

- The rational method, despite its simplicity, remains a valid and practical tool for hydrological design, provided that realistic and physically-consistent values are given to its parameters.
- For the regime of Cyprus, the runoff coefficients that are specified in the Greek Directives are overestimated, while the Giandotti formula for time of concentration is by far the only reliable.
- The proposed approach introduces the essential nonlinearity to the rational method, by depending both the runoff coefficient and the time of concentration to the return period.
- These preliminary results, based on a limited number of peak flows are encouraging, yet more research is necessary using the full time series of storm and flood events, which is in due course.

Acknowledgments – Contact info

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The presentation is available online at http://www.itia.ntua.gr/en/docinfo/1117/